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# High-Fidelity Device for Online Recording of Foot-Stretcher Forces During Rowing

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**Abstract**

Foot-stretcher forces have been identified as key variables determining rowing performance. The aim of this study was to develop an instrumented foot-stretcher. Under each forefoot, a six degrees of freedom sensor was mounted on an adjustable frame. Under each rearfoot, a one degree of freedom sensor was placed. Validation resulted in an accuracy of vertical forces of about 1% full scale. Sensor's crosstalk was up to 11% of vertical load. The instrumented foot-stretcher was integrated into a high-level rowing simulator. Propulsive foot-stretcher forces were displayed online and could be used as concurrent feedback about rowing performance.



*Keywords:* Instrumented Foot-Stretcher; Engineering Design; 3D Kinetics; Concurrent Feedback; Rowing Simulator

## 1. Introduction

The emphasis of elite athletes, whether amateur or professional, is upon preparation for, and execution of world beating performance [1]. Sports scientists and sports equipment manufacturers strive to develop technologies and products capable of yielding a competitive advantage to those utilising them [1]. In rowing, foot-stretcher forces have been identified as independent indicators of performance [2]. However, current devices measuring foot-stretcher forces have limited functionality and quantitative analyses have been performed only under limited conditions: measurements have been performed using ergometers wherein conditions differ substantially from on-water rowing [3], forces were only monitored along the longitudinal axis of the skiff, and forces were rarely measured beneath each foot independently, although sweep rowing is an asymmetrical movement (Table 1). In

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addition, athletes and coaches report preferential importance in the contribution of forces transmitted through the rearfoot when compared with the forefoot, yet no quantitative data has thus far been reported.

This work aimed to design an improved instrumented foot-stretcher that measures forces and torques beneath each forefoot in all three dimensions and in addition, vertical forces beneath each rearfoot. The forces should be displayed online in order to facilitate concurrent feedback about rowing performance that can be used for training both novice and elite rowers [4]. In the initial phase, the measuring device should be integrated into the M$^3$ Rowing Simulator (ETH Zurich, Switzerland), a simulator which serves as a high-level indoor training tool [5].

## 2. Methods

The device was designed in respect to the guidelines for Engineering Design of Pahl *et al.* [6]. The different design stages included (i) construction, (ii) manufacture, (iii) implementation, (iv) error analysis and (v) proof of functionality.

### *2.1. Construction*

The following requirements to measure foot-stretcher forces were identified by literature review and by discussions with Swiss elite rowers and a sports scientist, who has developed and used the Mobile Measuring System 2000 [7]: (i) independent monitoring of forces beneath each forefoot and rearfoot (ii) personalized adjustments of the instrumented foot-stretcher, and (iii) installation in different skiffs. The final measuring device should further meet the following requirements: accuracy of 1% full scale, crosstalk of less than 2% full scale, overload protection, high reliability, compact and robust design. The developed principal solution fulfilling these requirements was composed of two six degrees of freedom sensors (6 DOF) to determine forces and torques beneath the forefoot, and of two one degree of freedom sensors (1 DOF) to determine vertical forces beneath the rearfoot (Fig. 1). The required measuring range of the sensors (±0.7 kN; ±0.7 kN; ±1 kN; ±40 Nm; ±40 Nm; ±40 Nm) was also determined by literature review. Construction was completed through detailed working and assembly drawings, parts lists (Pro/Engineer Wildfire 3.0, Parametric Technology Corporation, USA), and through the work out of a circuit diagram (Microsoft Visio 2007, Microsoft Corporation, USA).

Table 1. Studies representing the state-of-the-art of foot-stretcher measuring devices

| Study | Type of rowing | Measuring device | Variables / Degrees of freedom (DOF) |
|---|---|---|---|
| MacFarlane *et al.* (1997) [8] | Ergometer | Strain gauges | Cumulative force, left and right / 1 DOF |
| Böhmert and Mattes (2003) [7] | On-water | Mobile Measuring System 2000 | Longitudinal force, both feet together / 1 DOF |
| Halliday *et al.* (2004) [9] | Ergometer | Multiaxial force transducer | Forces and torques, right foot / 6 DOF |
| Kleshnev (2004) [10] | On-water | Strain gauges | Longitudinal force, left and right foot / 1 DOF |
| Pudlo *et al.* (2005) [11] | Ergometer | Two 6-axis force platforms | Forces and torques, left and right foot / 6 DOF |
| Baca *et al.* (2006) [12] | Ergometer/On-water | Load cells and strain gauges | Horizontal and vertical forces, left and right foot / 2 DOF |
| Baca and Kornfeind (2008) [13] | Ergometer | Load cells and strain gauges | Horizontal and vertical forces, left and right foot / 2 DOF |

### 2.2. Manufacture

The device was produced and assembled in the affiliated workshop of the Institute of Robotics and Intelligent Systems, ETH Zurich. A 6 DOF sensor (Model K6D40S, ME-Messsysteme GmbH, Germany) was placed under each forefoot and a 1 DOF sensor (Model 31E01, Honeywell Sensotec, USA) was placed under each rearfoot. Both sensor models were based on strain gauges. The measuring range of the 6 DOF sensors was ±0.7 kN in the horizontal dimension, ±1 kN in the vertical dimension, and ±40 Nm around each orthogonal axis. The measuring range of the 1 DOF sensors was ±1 kN. The foot-stretcher was mounted into the rowing skiff of the M$^3$ Rowing Simulator (Fig. 2). The design of the device facilitates easy attachments to rowing skiffs, adjustments of shoe sizes from UK 8 to UK 14, and stretcher angles from 36° to 40°, as well as ab/adduction of the foot. The electronics of the newly developed measuring device was installed into a switch panel that was mounted onto the surrounding frame of the rowing skiff.

### 2.3. Implementation

The device was integrated into the existing M$^3$ Rowing Simulator setup [5]. 14 transducers (Model GSV1L, ME-Messsysteme GmbH, Germany) were used to acquire the analog signals representing the measured forces and torques of the sensors. These signals were digitized by two 8-channel A/D converter terminals (Model EL3008, Beckhoff Automation AG, Switzerland) that were connected with an EtherCAT Coupler (Model EK1100, Beckhoff Automation AG, Switzerland). Data was recorded by the xPC-Target using Matlab and Simulink (The MathWorks, USA). Forces can be displayed in the coordination system of the sensor ($\mathbf{CS}_{\mathbf{Sensor}}$), of the foot-stretcher ($\mathbf{CS}_{\mathbf{Stretcher}}$) or of the boat ($\mathbf{CS}_{\mathbf{Boat}}$) (Fig. 3).

### 2.4. Error analysis

Sensor forces were validated against a force gauge (AFG 1000, Mecmesin, UK) with an accuracy of ±0.1% full scale (Fig. 4). Vertical loads ranging from 20 N to 700 N were applied on the foot-stretcher sensors.

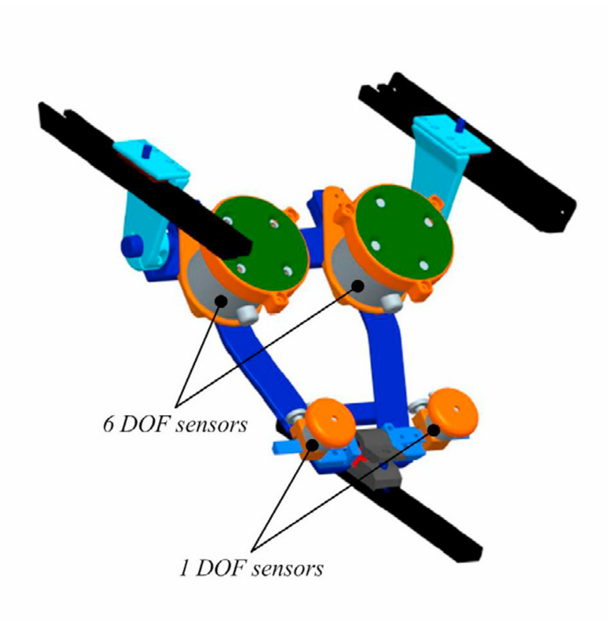


Fig. 1. CAD draft of the principal solution

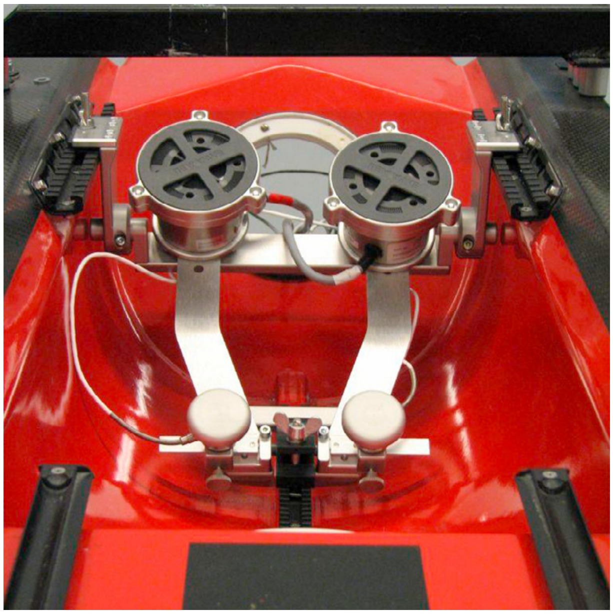

Fig. 2. New instrumented foot-stretcher mounted on the racks of the rowing skiff

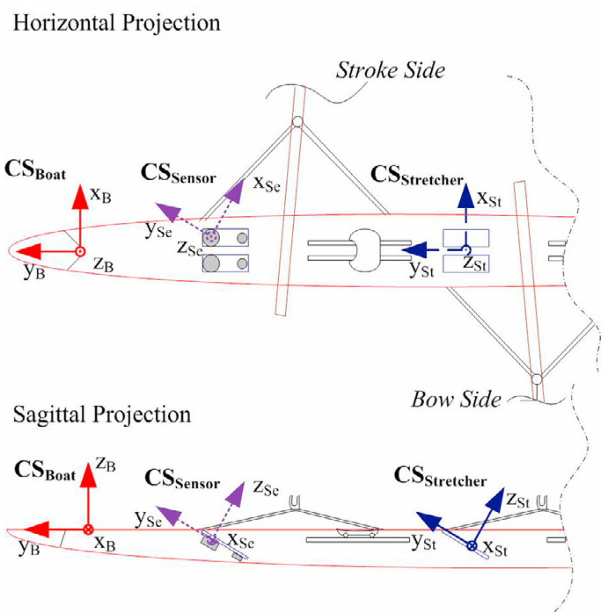


Fig. 3. Coordinate system of the $M^3$ Rowing Simulator

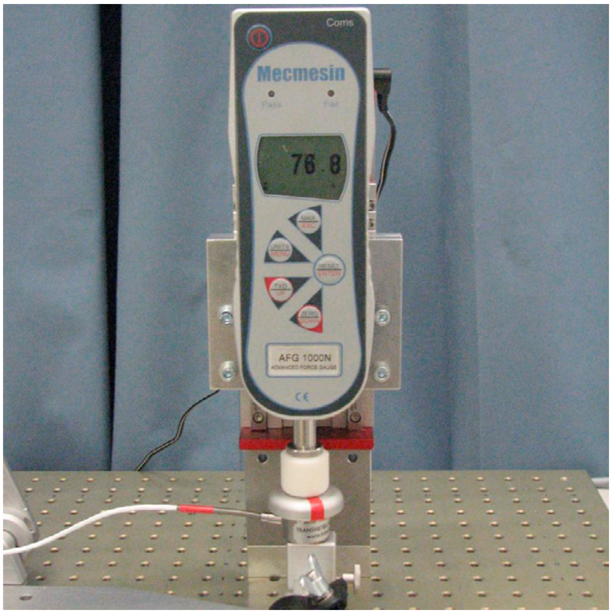


Fig. 4. Validation of the 1 DOF sensor forces with the force gauge (AFG)

The 1 DOF sensors were tested seven times with each load. Forces and torques of the 6 DOF sensors were measured once with each load, but seven times with 300 N. Means and standard deviations (*SD*) were determined for each measurement. Additionally, measured data, means and deviations of the left and right 1 DOF sensors were plotted. Measured data of vertical forces were used to perform a linear fit. The coefficient of determination ($R^2$) was calculated for each sensor.

### *2.5. Proof of functionality*

The functionality was proven by a measurement of a recreational rower rowing in the $M^3$ Rowing Simulator. Propulsive forces of the left and right forefoot and rearfoot were plotted online versus the horizontal angular displacement of the oar. The plots were displayed on a monitor in front of the rowing skiff to allow concurrent feedback about the rowing performance.

## 3. Results

The linear fit for the left 1 DOF sensor resulted in $R^2 = 0.99$ and for the right 1 DOF sensor in $R^2 = 1$ (Fig. 5). The according equation for the right 1 DOF sensor was $y = 1.01*x + 1.15$. The accuracy error was less than 1% full scale, i.e. less than 10 N. Linear fits of vertical forces for both 6 DOF sensors resulted in $R^2 = 1$ (Fig. 6). The equation of the linear fit for the right 6 DOF sensor was $y = 0.999*x + 0.423$. The standard deviation for the vertical force was in the magnitude of 0.4 N and 0.8 N for the left and right 6 DOF sensor, respectively (Table 2). The crosstalk of the 6 DOF sensors was up to 11% of the measured force and up to 5.1% when referring to full scale (Table 3). Measurements with the new $M^3$ Rowing Simulator setup including the instrumented foot-stretcher observed no difficulties during execution. Accelerated and decelerated propulsive foot-stretcher forces were continuously displayed against the horizontal angular displacement of the oar while rowing within the $M^3$ Rowing Simulator.

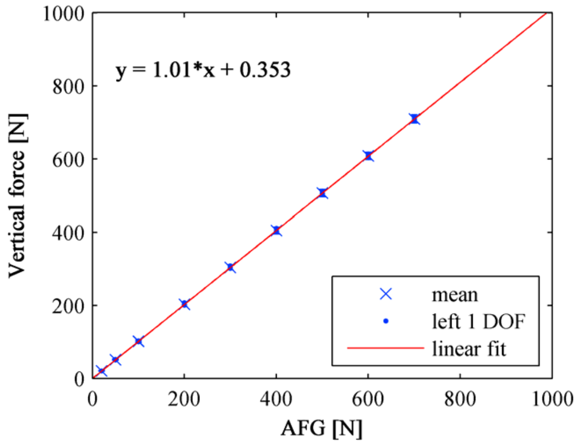


Fig. 5. Accuracy measurement of the left 1 DOF sensor using the AFG

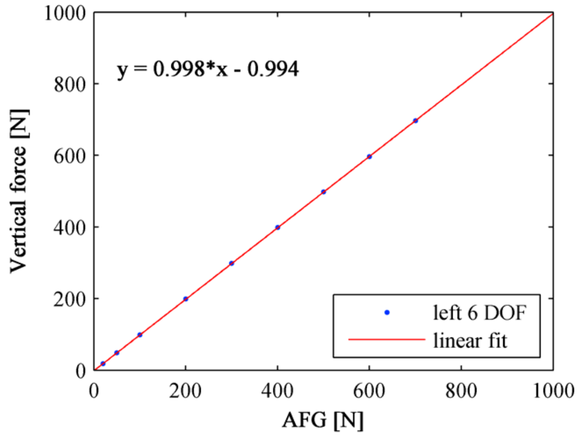


Fig. 6. Accuracy measurement of the left 6 DOF sensor using the AFG

Table 2. Repeatability measurements of the 6 DOF sensors with the force gauge (AFG) set to 300 N

| Left 6 DOF | Force [N] | | | Torque [Nm] | | | Right 6 DOF | Force [N] | | | Torque [Nm] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | x | y | z | x | y | z | | x | y | z | x | y | z |
| AFG 300 N | -20.9 | 9.4 | -298.5 | -0.9 | -1.8 | 0.0 | AFG 300 N | 15.3 | -12.4 | -299.6 | 0.8 | 1.9 | 0.0 |
| | -21.1 | 8.5 | -299.6 | -0.7 | -1.9 | 0.0 | | 14.7 | -13.0 | -301.6 | 0.8 | 2.1 | 0.0 |
| | -21.0 | 8.5 | -298.9 | -0.7 | -1.9 | 0.0 | | 14.6 | -13.3 | -300.7 | 0.7 | 2.1 | 0.0 |
| | -20.0 | 9.3 | -298.9 | -0.6 | -1.8 | 0.0 | | 14.7 | -13.1 | -300.3 | 0.7 | 2.1 | 0.0 |
| | -20.8 | 9.0 | -299.1 | -0.7 | -1.8 | 0.0 | | 14.8 | -12.7 | -300.7 | 0.7 | 2.1 | 0.0 |
| | -20.9 | 9.2 | -298.7 | -0.8 | -1.8 | 0.0 | | 14.8 | -12.8 | -299.4 | 0.8 | 1.8 | 0.0 |
| | -20.8 | 9.3 | -299.4 | -0.8 | -1.9 | 0.0 | | 14.3 | -12.6 | -300.0 | 0.6 | 1.8 | 0.0 |
| Mean | -20.8 | 9.0 | -299.0 | -0.7 | -1.8 | 0.0 | Mean | 14.7 | -12.8 | -300.3 | 0.7 | 2.0 | 0.0 |
| SD | 0.4 | 0.4 | 0.4 | 0.1 | 0.1 | 0.0 | SD | 0.3 | 0.3 | 0.8 | 0.1 | 0.2 | 0.0 |

Table 3. Accuracy measurements of the 6 DOF sensors at different vertical loads applied with the force gauge (AFG)

| Left 6 DOF | | | | | | | Right 6 DOF | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AFG [N] | Force [N] | | | Torque [Nm] | | | AFG [N] | Force [N] | | | Torque [Nm] | | |
| | x | y | z | x | y | z | | x | y | z | x | y | z |
| 20 | -2.2 | 0.5 | -18.3 | -0.1 | -0.1 | 0.0 | 20 | 0.5 | -1.2 | -20.3 | 0.1 | 0.1 | 0.0 |
| 50 | -4.5 | 2.0 | -48.5 | -0.2 | -0.3 | 0.0 | 50 | 1.9 | -3.0 | -49.7 | 0.2 | 0.3 | 0.0 |
| 100 | -7.8 | 3.6 | -98.9 | -0.4 | -0.7 | 0.0 | 100 | 4.7 | -5.3 | -100.5 | 0.3 | 0.7 | 0.0 |
| 200 | -14.6 | 6.9 | -199.6 | -0.7 | -1.3 | 0.0 | 200 | 9.9 | -9.3 | -200.7 | 0.6 | 1.3 | 0.0 |
| 300 | -20.9 | 9.4 | -298.5 | -0.9 | -1.8 | 0.0 | 300 | 15.3 | -12.4 | -299.6 | 0.8 | 1.9 | 0.0 |
| 400 | -26.4 | 10.8 | -398.5 | -1.0 | -2.4 | 0.0 | 400 | 20.1 | -14.5 | -401.0 | 0.9 | 2.5 | 0.0 |
| 500 | -31.1 | 11.7 | -497.9 | -1.1 | -2.8 | 0.0 | 500 | 24.3 | -14.8 | -499.3 | 0.8 | 3.0 | 0.0 |
| 600 | -34.0 | 12.0 | -597.1 | -1.1 | -3.1 | 0.1 | 600 | 26.9 | -13.8 | -600.3 | 0.7 | 3.5 | 0.0 |
| 700 | -35.6 | 10.8 | -697.4 | -1.1 | -3.1 | 0.1 | 700 | 28.5 | -11.5 | -698.8 | 0.4 | 3.8 | 0.1 |

## 4. Discussion

According to the guidelines for Engineering Design [6], we were successful in designing an improved device for measuring foot-stretcher forces that overcomes the limitations of current state-of-the-art devices and moreover fits the needs of its future users. It is the first time that an instrumented foot-stretcher is capable of independently measuring online foot-stretcher forces and torques beneath each forefoot in all dimensions, and in addition, vertical forces beneath each rearfoot. Furthermore, personalized settings of the foot-stretcher are not constrained by the device. The accuracy error of the instrumented foot-stretcher for vertical forces was 1% full scale, and hence met the requirements of accuracy. Whereas measurements of pure vertical loads yielded horizontal forces in a less satisfactory magnitude of up to 11% of the vertical load, thus pretending the occurrence of horizontal foot-stretcher forces that were nonexistent. Therefore, the following steps are suggested to improve the accuracy of the device: (i) recalibration of the 1 DOF sensors offset by usage of the equations of the linear fits, (ii) validation of the 6 DOF sensors with multi-dimensional loads and (iii) determination and usage of correction factors based on the results of the new validation.

Nevertheless, the device could already be used for measurements in the $M^3$ Rowing Simulator within a setup that simulates on-water rowing under laboratory conditions. Subsequently, the instrumented foot-stretcher will contribute to the optimization of the individual rowing technique. For instance, individual settings of the foot-stretcher can now quantitatively be correlated to propulsive or undesired foot-stretcher forces. With the ability to provide online measurements, this sophisticated device can deliver accurate information to elite rowers and coaches helping them to detect “errors in a performance that is already proficient” [2, p. 784].

## 5. Outlook

In a next step, after finishing the accuracy improvements, effects of different settings of the foot-stretcher, e.g. adjustment of stretcher angles, will be systematically evaluated with respect to accelerating and decelerating foot-stretcher forces. In the long run, power support and data transmission will be modified to enable on-water measurements.

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